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Indian Standard

OPTICAL FIBRES

PART 1 MEASUREMENT METHODS AND TEST PROCEDURES

Section 45 Mode Field Diameter

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Fibre Optics, Fibres, Cables and Devices Sectional Committee, LITD 11

NATIONAL FOREWORD

This Indian Standard (Part 1/Sec 45) which is identical with IEC 60793-1-45 : 2001 'Optical fibres — Part 1-45: Measurement methods and test procedures — Mode field diameter' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Fibre Optics, Fibres, Cables and Devices Sectional Committee and approval of the Electronics and Information Technology Division Council.

The text of IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60793-1-40 : 2001 Optical fibres — Part 1-40: Measurement methods and test procedures — Attenuation	IS/IEC 60793-1-40 : 2001 Optical fibres: Part 1 Measurement methods and test procedures, Section 40 Attenuation	Identical
IEC 60793-2 : 1998[1] Optical fibres — Part 2: Product specifications	IS/IEC 60793-2 : 2007 Optical fibres: Part 2 Product specifications — General	Technically Equivalent

Only the English language text has been retained while adopting it in this Indian Standard and as such the page numbers given here are not the same as in the IEC Publication.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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[1] Since revised in 2007.

Indian Standard

OPTICAL FIBRES

PART 1 MEASUREMENT METHODS AND TEST PROCEDURES

Section 45 Mode Field Diameter

1 Scope

This part of IEC 60793 establishes uniform requirements for measuring the mode field diameter (MFD) of optical fibre, thereby assisting in the inspection of fibres and cables for commercial purposes.

The MFD represents a measure of the transverse extent of the electromagnetic field intensity of the mode in a fibre cross section, and it is defined from the far-field intensity distribution as a ratio of integrals known as the Petermann II definition. See equation (1).

The definitions of MFD are strictly related to the measurement configurations. The mathematical equivalence of these definitions results from transform relationships between measurement results obtained by different implementations summarized in figure 1 as follows:

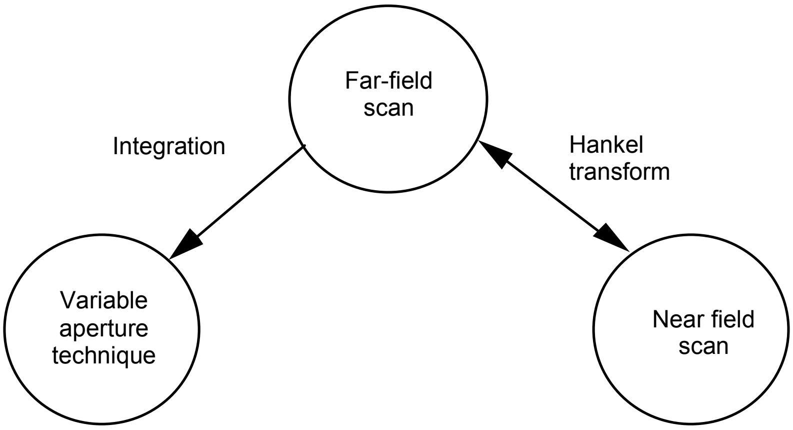


Figure 1 – Transform relationships between measurement results

Four methods are described for measuring MFD:

- method A: direct far-field scan;
- method B: variable aperture in the far field;
- method C: near-field scan;
- method D: bi-directional backscatter using an optical time domain reflectometer (OTDR).

All four methods apply to all categories of type B single-mode fibre shown in IEC 60793-2 and operating near 1 310 nm or 1 550 nm. Method D is not recommended for the measurement of fibres of unknown type or design.

Information common to all four methods is contained in clauses 1 to 8, and information pertaining to each individual method appears in annexes A, B, C and D, respectively.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 60793. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of IEC 60793 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60793-1-40, *Optical fibres – Part 1-40: Measurement methods and test procedures – Attenuation*

IEC 60793-2:1998, *Optical fibres – Part 2: Product specifications*

3 Reference test method

Method A, direct far-field scan, is the reference test method (RTM), which shall be the one used to settle disputes.

4 Apparatus

The following apparatus is common to all measurement methods. Annexes A, B, C and D include layout drawings and other equipment requirements for each of the four methods, respectively.

4.1 Light source

For methods A, B and C, use a suitable coherent or non-coherent light source such as a semiconductor laser or a sufficiently powerful filtered white light source. The source shall produce sufficient radiation at the intended wavelength(s) and be stable in intensity over a time period sufficient to perform the measurement.

A monochromator or interference filter(s) may be used, if required, for wavelength selection. The detail specification shall specify the wavelength of the source. The FWHM (full width half maximum) spectral line width of the source shall be less than or equal to 10 nm, unless otherwise specified.

See annex D for method D.

4.2 Input optics

For method A, B, and C, an optical lens system or fibre pigtail may be employed to excite the specimen. It is recommended that the power coupled into the specimen be relatively insensitive to the position of its input end face. This can be accomplished by using a launch beam that spatially and angularly overfills the input end face.

If using a butt splice, employ index-matching material between the fibre pigtail and the specimen to avoid interference effects. The coupling shall be stable for the duration of the measurement.

See annex D for method D.

4.3 Input positioner

Provide means of positioning the input end of the specimen to the light source. Examples include the use of x-y-z micropositioner stages, or mechanical coupling devices such as connectors, vacuum splices, three-rod splices, etc. The position of the fibre shall remain stable over the duration of the measurement.

4.4 Cladding mode stripper

Use a device that extracts cladding modes. Under some circumstances the fibre coating will perform this function.

4.5 High-order mode filter

Use a means to remove high-order propagating modes in the wavelength range that is greater than or equal to the cut-off wavelength of the specimen. For example, a one-turn bend with a radius of 30 mm on the fibre is generally sufficient.

4.6 Output positioner

Provide a suitable means for aligning the fibre output end face in order to allow an accurate axial adjustment of the output end, such that, at the measurement wavelength, the scan pattern is suitably focused on the plane of the scanning detector. Such coupling may include the use of lenses, or may be a mechanical connector to a detector pigtail.

Provide means such as a side-viewing microscope or camera with a crosshair to locate the fibre at a fixed distance from the apertures or detectors. It may be sufficient to provide only longitudinal adjustment if the fibre is constrained in the lateral plane by a device such as a vacuum chuck. (This depends mainly upon the size of the light detector.)

4.7 Output optics

See the appropriate annex: A, B, C or D.

4.8 Detector

See the appropriate annex: A, B, C or D.

4.9 Computer

Use a computer to perform operations such as controlling the apparatus, taking intensity measurements, and processing the data to obtain the final results. For individual details, see the appropriate annex: A, B, C or D.

5 Sampling and specimens

5.1 Specimen length

For methods A, B and C, the specimen shall be a known length, typically 2 m ± 0,2 m of single-mode fibre.

NOTE For method D, OTDR, the sample must be long enough to exceed (or be positioned beyond) the dead zone of the OTDR, with both ends accessible, as described in the backscatter test method IEC 60793-1-40.

5.2 Specimen end face

Prepare a flat end face, orthogonal to the fibre axis, at the input and output ends of each specimen.

6 Procedure

See annex A, B, C and D for methods A, B, C and D, respectively.

7 Calculations

The basic equations for calculating MFD by methods A, B and C are given below. For additional calculations, see the appropriate annex: A, B, C or D. Sample data sets for methods A, B and C are included in annex E.

7.1 Method A – Direct far-field scan

The following equation defines the MFD for method A in terms of the electromagnetic field emitted from the end of the specimen.

Calculate the MFD by scanning the far-field data and evaluating the Petermann II integral, which is defined from the far-field intensity distribution:

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi}\left[\frac{\int_0^{\pi/2} P_F(\theta)\sin(\theta)\cos(\theta)\mathrm{d}\theta}{\int_0^{\pi/2} P_F(\theta)\sin^3(\theta)\cos(\theta)\mathrm{d}\theta}\right] \tag{1}$$

where

$2W_0$ is the MFD in µm;

$P_F(\theta)$ is the far-field intensity distribution;

λ is the wavelength of measurement in µm;

θ is the angle in the far-field measurement from the axis of the fibre.

NOTE 1 The integration limits are shown to be from zero to $\pi/2$, but it is understood that the integrands approach zero with increasing argument so that, in practice, the integrals can be truncated.

NOTE 2 P_F is the $F^2(\theta)$ in ITU-T publications.

The far-field method for obtaining the MFD of a single-mode fibre is a two-step procedure. First, measure the far-field radiation pattern of the fibre. Second, use a mathematical procedure based on the Petermann II far-field definition to calculate the mode field from far-field data, as described in equation (1) above.

Annex E provides sample data and calculated values for $2W_0$ to enable one to check the numerical evaluation of the Petermann II Integral. The sample data are in the form of the folded power, $P_F(\theta)$, as a function of the angle, θ.

7.2 Method B – Variable aperture in the far field

The following equations define the MFD for method B in terms of the electromagnetic field emitted from the end of the specimen.

Calculate the MFD, $2W_0$, as follows:

$$2W_0 = \left(\frac{\lambda}{\pi D}\right)\left[\int_0^{\infty} a(x)\frac{x}{\left(x^2 + D^2\right)^2}\,\mathrm{d}x\right]^{1/2} \tag{2}$$

where

$2W_0$ is the MFD, in µm;

λ is the wavelength of measurement, in µm;

D is the distance between the aperture and the fibre, in mm;

$a(x)$ is the complementary aperture transmission function, calculated as

$$a(x) = 1 - \frac{P(x)}{P(\max)} \tag{3}$$

where

$P(x)$ is the power measured through an aperture of radius, x, or half angle, θ;

$P(\max)$ is the maximum power, assuming an infinite aperture;

x is the aperture radius, calculated as

$$x = D\tan(\theta) \tag{4}$$

where D is the distance between the aperture and the fibre, in mm.

The mathematical equivalence of equations (1) and (2) is valid in the approximation of small angles, θ. Under this approximation, equation (2) can be derived from equation (1) by integration. Another equivalent expression of equation (2) is:

$$2W_0 = \frac{\lambda\sqrt{2}}{\pi}\left[\int_0^{\infty} a(\theta)\sin 2\theta\,\mathrm{d}\theta\right]^{1/2} \tag{5}$$

where

$2W_0$ is the MFD, in µm;

$a(\theta)$ is the complementary aperture function, calculated as

$$a(\theta) = 1 - \frac{P(\theta)}{P(\max)} \tag{6}$$

where

$P(\theta)$ is the power through the largest aperture;

$P(\max)$ is the maximum power, assuming an infinite aperture.

The variable aperture far-field method for obtaining the MFD of a single-mode fibre is a two-step procedure. First, measure the two-dimensional far-field pattern as the power passing through a series of transmitting apertures of various size. Second, use a mathematical procedure to calculate the MFD from the far-field data.

The mathematical basis for the calculation of MFD is based on the Petermann II far-field definition from equation (1). The mathematical equivalence of equations (1) and (3) is valid in the approximation of small angles, θ. Derive equation (5) from equation (1) by integration.

7.3 Method C – Near-field scan

The following equation defines the MFD for method C in terms of the electromagnetic field emitted from the end of the specimen.

Calculate the MFD from the measured near-field intensity distribution, using the following integral:

$$2W_0 = 2\left[2\frac{\int_0^\infty r\ f^2(r)\mathrm{d}r}{\int_0^\infty \left(\frac{\mathrm{d}f(r)}{\mathrm{d}r}\right)^2 \mathrm{d}r}\right] \qquad (7)$$

where

$2W_0$ is the MFD, in µm;

r is the radial coordinate, in µm;

$f^2(r)$ is the near-field intensity distribution.

NOTE The upper integration limits is shown to infinity, but it is understood that since the integrands approach zero with increasing argument, in practice the integrals can be truncated. A smoothing algorithm can be used for the calculation of the derivative.

The near-field scan method for obtaining the MFD of a single-mode fibre is a two-step procedure. First, measure the radial near-field pattern. Second, use a mathematical procedure to calculate the MFD from the near-field data.

The mathematical basis for the calculation of the MFD is based on the Petermann II definition from equation (1). The mathematical equivalence of equations (1) and (5) is valid in the approximation of small angles, θ. Under this approximation, the near field, $f(r)$, and the far field, $F(\theta)$, form a Hankel pair. By means of the Hankel transformation it is possible to pass from equation (1) to equation (7), and reverse.

8 Results

8.1 Information to be provided with each measurement

Report the following information with each measurement:

- date and title of measurement;
- identification of specimen;
- optical source wavelength;
- MFD(s), in µm.

8.2 Information available upon request

The following information shall be available upon request:

- measurement method used: A, B, C or D;
- type of optical source used and its spectral width (FWHM);

- description of equipment;
- details of computation technique;
- date of latest calibration of measurement equipment.

9 Specification information

The detail specification shall specify the following information:

- type of fibre to be measured;
- failure or acceptance criteria;
- information to be reported;
- any deviations to the procedure that apply.

Annex A
(normative)

Requirements specific to method A – Mode field diameter by direct far-field scan

A.1 Apparatus

This annex describes apparatus in addition to the requirements set down in clause 4.

Figure A.1 illustrates a typical set-up for measurement by direct far-field scan.

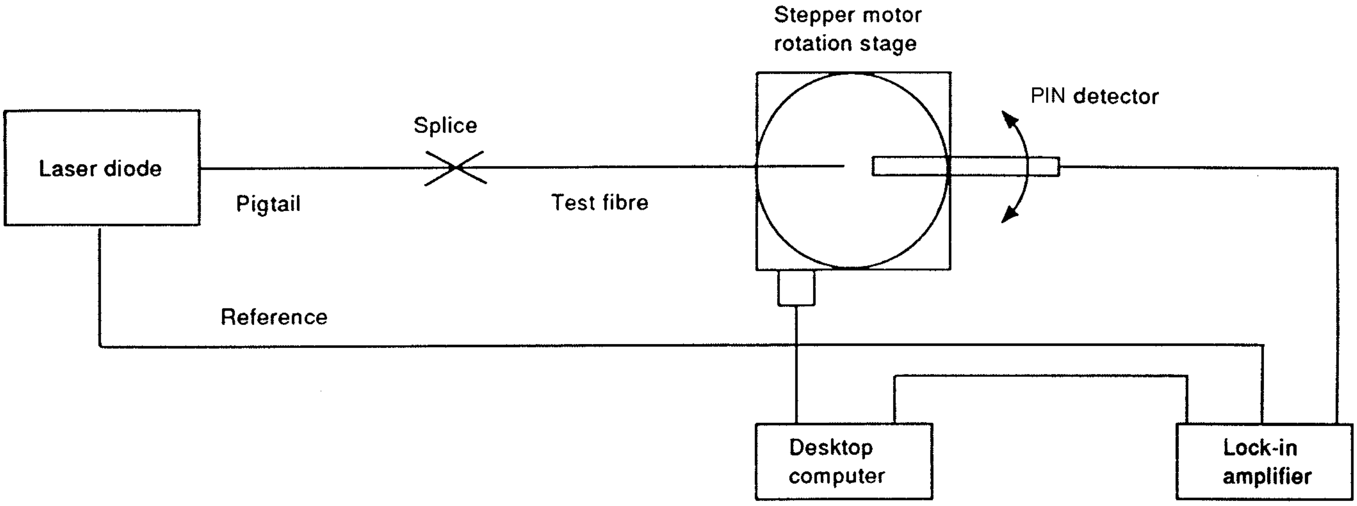


Figure A.1 – Far-field measurement set

A.1.1 Scanning detector assembly – Signal detection electronics

Use a mechanism to scan the far-field intensity distribution. Use a scanning device capable of 0,50° steps or finer to scan the detector. Use a means of aligning the fibre axis with respect to the rotation plane of the detector, and of aligning the fibre end-face with the centre of rotation of the scan. A typical system might include a PIN photodiode, operating in a photovoltaic mode, amplified by a current-input preamplifier, with synchronous detection by a lock-in amplifier. The detector should be at least 10 mm from the fibre end, and the detector's active area should not subtend too large an angle in the far field. To ensure this, place the detector at a distance from the fibre end greater than $2wb/\lambda$, where $2w$ is the expected MFD of the specimen and b is the diameter of the active area of the detector.

For very accurate measurements, the minimum dynamic range of the measurement should be 50 dB. This corresponds to a maximum scan half-angle of 20° and 25°, or greater, for category B1 and B2 fibres, respectively. Reducing the dynamic range (or maximum scan half-angle) requirements may introduce errors. For example, restricting those values to 30 dB and 12,5° for category B1 fibres, and to 40 dB and 20° for category B2 fibres, may result in a relative error, in the determination of the MFD, that is greater than 1 %.

A.1.2 Computer

A typical system should also include a computer to process the far-field data.

A.2 Procedure

Align the fibre in the system, prepared as described in 4.2, with its output end aligned on the detector assembly for maximum power.

Scan the detector in 0,5° steps, equally spaced, and record the detector power.

Calculate a value of the Petermann II integral from the recorded data, and use it to compute the fibre MFD as described in equation (1), and in A.3.

A.3 Calculations

A.3.1 Determine folded power curve

The folded power curve for $0 \leq \theta_i = \theta_{max}$ is

$$P_F(\theta_i) = \frac{P(\theta_i) + P(\theta_{-i})}{2} \tag{A.1}$$

where

$P_F(\theta_i)$ is the folded power curve;

$P(\theta_{-i})$ is the measured power as a function of the angular position, θ_i (radians), indexed by *i.*

A.3.2 Compute the top (*T*) and bottom (*B*) integrals of equation (1)

Use an appropriate numerical integration technique to compute the integrals of equation (1). The following is an example using the rectangular method. Any other integration method shall be at least as accurate.

$$T = \sum_0^n P_F(\theta_i) \sin(\theta_i) \cos(\theta_i) \, d\theta \tag{A.2}$$

$$B = \sum_0^n P_f(\theta_i) \sin^3(\theta_i) \cos(\theta_i) \, d\theta \tag{A.3}$$

where

P_f is the folded power curve;

θ_i is the angular position, indexed by *i* (radians);

where $d\theta = \theta_1 - \theta_0$.

A.3.3 Complete the calculation

$$\mathrm{MFD} = 2W_0 = \left(\frac{\lambda\sqrt{2}}{\pi}\right)\sqrt{\frac{T}{B}} \tag{A.4}$$

where

$2W_0$ is the MFD, in µm;

T is obtained from equation (A.2);

B is obtained from equation (A.3).

A.4 Sample data

See table E.1 for a sample data set as calculated in A.3.

Annex B
(normative)

Requirements specific to method B – Mode field diameter by variable aperture in the far field

B.1 Apparatus

This annex describes apparatus in addition to the requirements in clause 4.

Figure B.1 illustrates a typical set-up for the measurement by variable aperture in the far field.

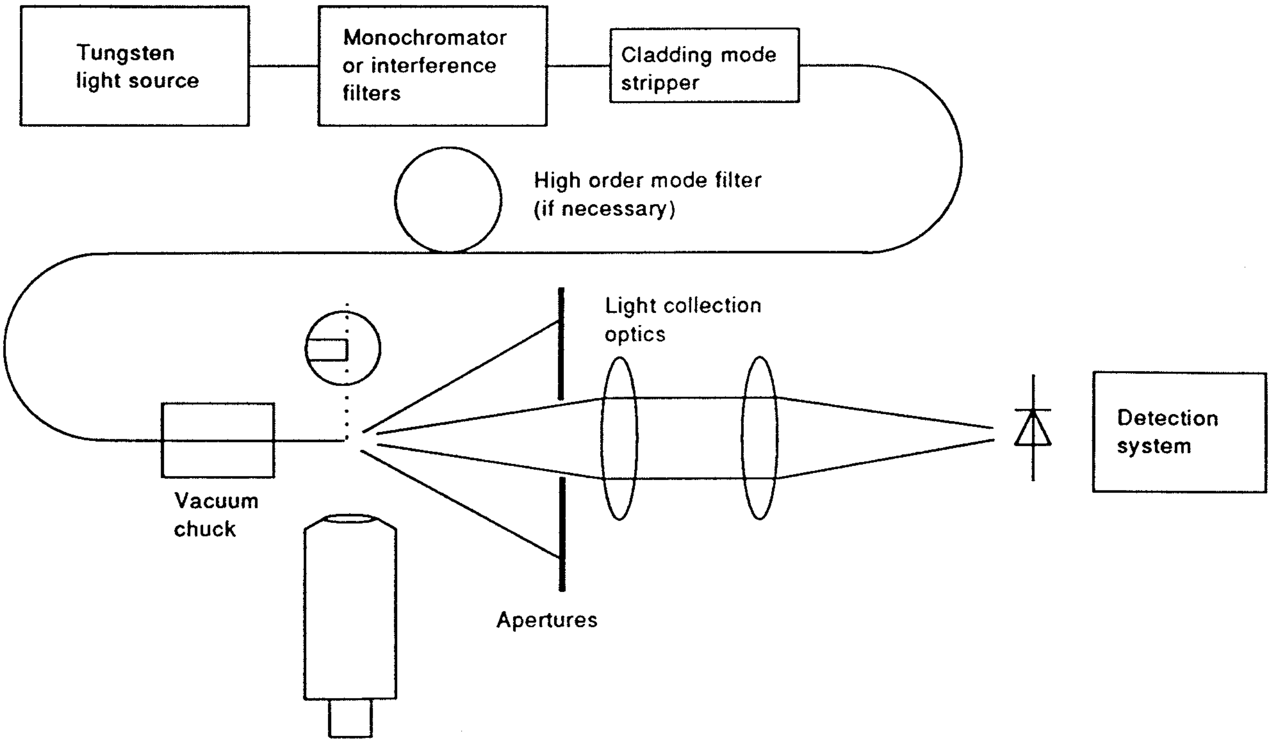


Figure B.1 – Variable aperture by far-field measurement set

B.1.1 Output variable aperture assembly

Place a device consisting of round, transmitting apertures of various sizes (such as an aperture wheel) at a distance of at least 100 W_0^2/λ from the specimen, and use it to vary the power detached from the fibre output far field pattern. Typically, the apertures are located 20 mm to 50 mm away from the fibre end.

Use a means of centering the apertures with respect to the pattern in order to decrease the sensitivity to fibre end angle. Use a sufficient number and size of apertures such that the measurement results are not unduly affected by the inclusion of any additional aperture. In addition, take care to ensure that the largest apertures are of sufficient size to avoid truncation of the collected pattern.

NOTE 1 Optical alignment is critical.

NOTE 2 The number and size of the apertures are critical to the accuracy of this method. The optimum can vary depending on the design of the fibres being tested. Verification of a particular selection can be completed by comparison with method A, direct far-field.

B.1.1.1 Equipment requirements for category B1 fibre

The accuracy of the MFD measurement given by this procedure depends on the maximum numerical aperture of the measurement set. For category B1 fibre, the error is typically 1 % or less for a measurement set with a maximum numerical aperture of 0,25. If less error is desired, or if the specimen has a MFD less than 8,2 µm, use either of two approaches:

a) use a measurement system with a maximum numerical aperture of 0,35 or greater; or

b) determine a mapping function that relates the measurement of category B1 fibre on limited aperture measurement set to that of a set with 0,35 or greater numerical aperture.

B.1.1.2 Equipment requirements for category B2, B3, and B4 fibres

The maximum numerical aperture of the measurement set shall be equal to or greater than 0,40 for fibres with MFDs equal to or greater than 6 µm.

B.1.2 Output optics system

Use an optical system, such as a pair of lenses, mirrors, or other suitable arrangement, to collect all the light transmitted through the aperture, and to couple it to the detector.

B.1.3 Detector assembly and signal detection electronics

Use a detector that is sensitive to the output radiation over the range of wavelengths to be measured and that is linear over the range of intensities encountered. A typical system might include a germanium or GaInAs photodiode, operating in the photovoltaic mode, and a current-sensitive preamplifier, with synchronous detection by a lock-in amplifier. Generally, a computer is required to analyze the data.

B.2 Procedure

B.2.1 Place the specimen, prepared as described in 4.2, in the input and output alignment devices, and adjust it for the correct distance to the aperture assembly.

B.2.2 Set the aperture assembly to a small aperture, and adjust the far field to an aperture lateral alignment for maximum detected power.

B.2.3 Measure the detected power for each of the apertures.

B.2.4 Repeat B.2.3 for each specified measurement wavelength.

B.2.5 Calculate the MFD per equation (2) and B.3.

B.3 Calculations

B.3.1 Determine complementary aperture function

Determine the complementary aperture function for each aperture, from 1 to *n:*

$$a(\theta_\mathrm{i}) = 1 - \frac{P(\theta_\mathrm{i})}{P(\theta_\mathrm{n})} \qquad \text{(B.1)}$$

where

$a(\theta_\mathrm{i})$ is the complementary function for each aperture, indexed with *i*, from 1 to *n*;

$P(\theta_\mathrm{i})$ is the measured power as a function of the angular position, θ_i, indexed by *i*.

B.3.2 Complete the integration

Use an appropriate numerical integration technique to compute the integrals of equation (5). The following is an example. Any other integration method shall be at least as accurate.

$$T = \sum_{1}^{n} a(\theta_\mathrm{i})\sin(2\theta_\mathrm{i})(\theta_\mathrm{i} - \theta_\mathrm{i-1}) \qquad \text{(B.2)}$$

where

T is the top integral of equation (1);

$a(\theta_\mathrm{i})$ is the complementary aperture function from equation (B.1).

NOTE $\theta_0 = 0$.

B.3.3 Complete the calculation

$$\mathrm{MFD} = 2W_0 = \left(\frac{\lambda}{\pi}\right)\sqrt{\frac{2}{T}} \qquad \text{(B.3)}$$

where

$2W_0$ is the MFD, in µm;

T is from equation (B.2).

B.4 Sample data set

See table E.2 for a sample data set as calculated in B.3.

Annex C
(normative)

Requirements specific to method C –
Mode field diameter by near-field scan

C.1 Apparatus

This annex describes apparatus in addition to the requirements in clause 4.

Figure C.1 illustrates a typical set-up for the measurement by near-field scan.

C.1.1 Magnifying output optics

Use a suitable optical system (for example a microscopic objective) to magnify the output end of the specimen, focusing it onto the plane of the scanning detector. These optics shall not restrict the numerical aperture of the formed image and shall have a numerical aperture greater than the maximum NA of the fibre output radiation and not less than 0,45 for B2 and B3 fibres, and not less than 0,35 for B1 fibres.

C.1.2 Scanning detector

Use a suitable scanning detector to measure the point-to-point intensity of the transmitted near field pattern. The detector shall be linear over the range of intensities encountered.

Use a scanning system (mechanical or electronic) that permits a suitable resolution of the near-field image (typically 100 points or more along a range of the near-field pattern, which is about three times the nominal MFD reported to the fibre surface).

For example, any of the following techniques can be used:

a) a fixed photo detector in which the field is scanned by a scanning pigtail fibre;
b) a scanning vidicon, charge-coupled devices (CCD) or other pattern/intensity recognition devices.

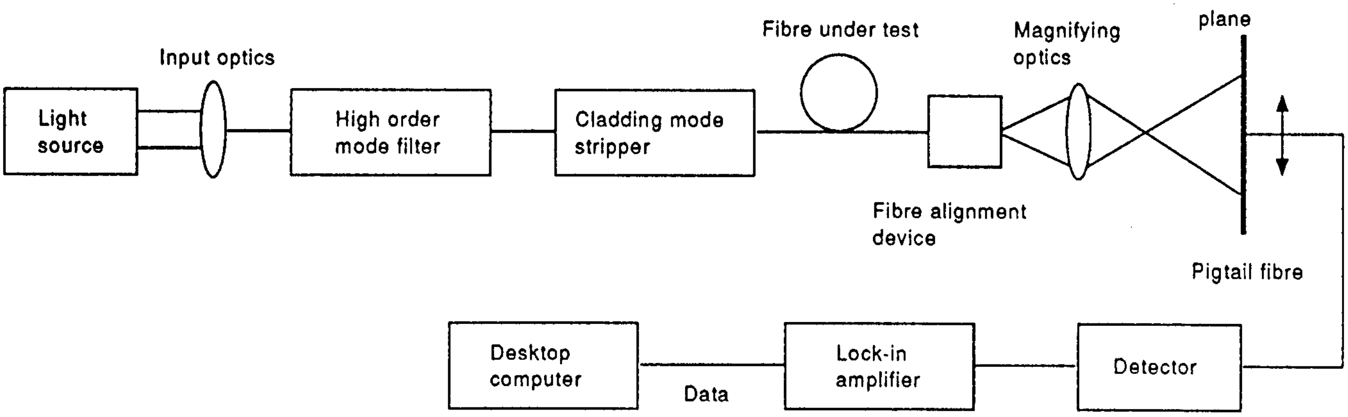
Accurately calibrate such devices in position.

C.1.3 Detection electronics

In order to increase the signal level, use a suitable electronic system. Choose the bandwidth of such an electronic system according to type of technique used.

When scanning the output end of the fibre with a mechanical or optical system, it is customary to modulate the optical source. If adopting such a procedure, link the amplifier (for example lock-in amplifier) to the source modulation frequency. When performing the scanning electronically, use a suitable video analyzing system and a system for automatic scanning of the near-field image, data acquisition, and processing.

a) Mechanical scanning



b) Electronic scanning

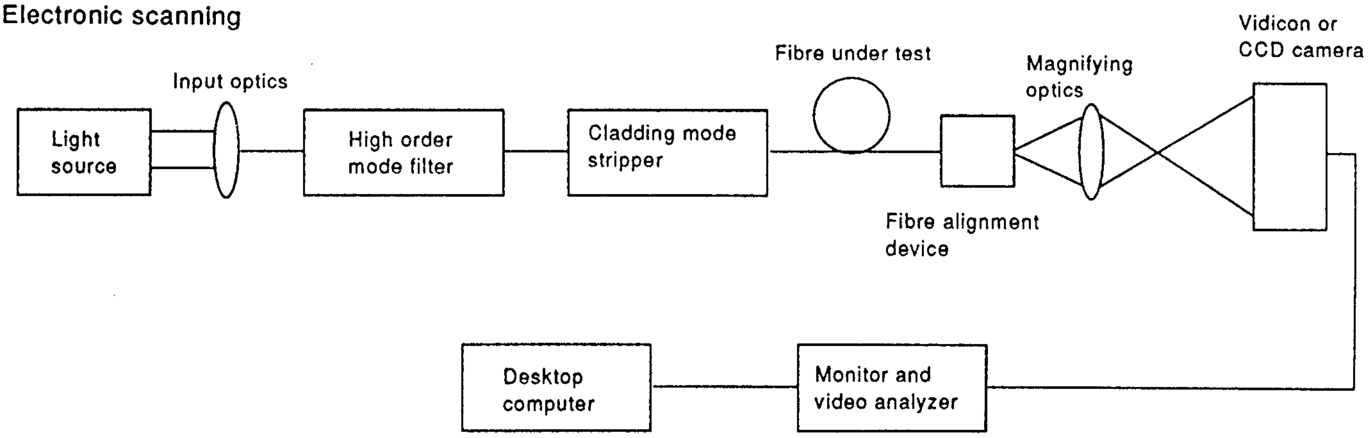


Figure C.1 – Near-field measurement set-ups

C.2 Procedure

C.2.1 Place the specimen, prepared as described in 4.2, in the input and output alignment devices, and adjust it for correct distance to the magnifying optics in such a way as to be focused onto the plane of the scanning detector. The criterion of maximizing the contrast of the image can be used for a proper focus.

C.2.2 Either scan the magnified near-field pattern by moving the scanning fibre and recording the detected intensity as a function of position, or process the near-field pattern by means of a video analyzer, according to whether the scanning is mechanical or electronic, respectively.

C.2.3 Calculate the value of the MFD from the near-field intensity pattern, $f^2(r)$, expressed on the fibre output face, taking into account the magnification and the actual radial coordinate, r, according to C.3.

C.2.4 Periodically measure the magnification of the magnifying optics in conjunction with the scanning system. Perform the initial calibration using a suitable calibrated grating, and then periodically check it by scanning the image of a fibre end face whose dimensions are known with suitable accuracy.

C.3 Calculations

C.3.1 Calculate the centroid

For a given cross section of the near-field test pattern that is of maximum extent, calculate the centroid position as follows:

$$r_c = \frac{\sum r_i f^2(r_i)}{\sum f^2(r_i)} \tag{C.1}$$

where

r_c is the centroid position;

r_i are the position values;

$f^2(r_i)$ are the intensity values.

C.3.2 Fold the intensity profile

Re-index the position and intensity data around the position centroid from equation (C.1) so that positions above have index values greater than zero, and positions below have index values less than zero. The maximum index is given as n. The folded index profile is

$$f_f^2(r_i) = \left[\frac{f^2(r_i) + f^2(r_{-i})}{2}\right] \tag{C.2}$$

where

$f_f^2(r_i)$ is the folded intensity value;

$f^2(r_i)$ are the intensity values.

C.3.3 Compute the integrals

Use an appropriate numerical integration technique to compute the integrals of equation (7). The following is an example. Any other integration method shall be at least as accurate.

Compute the top and bottom integrals of equation (7) as follows:

$$T = \sum_{0}^{n} r_i \; f_f^2(r_i)\, dr \tag{C.3}$$

where

T is the top integral of equation (3);

r_i are the position values;

$f_f^2(r_i)$ are the folded intensity profiles.

$$B = \sum_{0}^{n} r_i \left[\frac{df_f(r_i)}{dr} \right] dr \tag{C.4}$$

where

B is the bottom integral of equation (3);

$df_f(r_i) = f_f(r_i) - f_f(r_{i-1})$ for $i > 0$, or 0 for $i = 0$;

$dr = (r_1 - r_0)$.

NOTE The data may be fitted to a curve for the computation of the derivative.

C.3.4 Complete the calculation

$$\text{MFD} = 2W_0 = 2\sqrt{\frac{2T}{B}} \tag{C.5}$$

where

$2W_0$ is the MFD in µm;

T is from equation (C.3);

B is from equation (C.4).

Annex D
(normative)

Requirements specific to method D – Mode field diameter by optical time domain reflectometer (OTDR)

This method describes the calculation of MFD at the fibre ends using the results of bi-directional backscatter measurements from an optical time domain reflectometer (OTDR).

The measurement is made by comparison to a reference pigtail fibre with a known value of MFD at the pigtail fibre ends. This reference fibre should be of a similar single-mode design as the fibre that is being characterized, for example, matched cladding B1 type fibre. An empirical mapping can sometimes be used for characterization of a fibre of one design with a reference fibre of another design. This mapping is specific to the design pair.

The measurement is limited to MFD at the reference-sample joint because OTDRs are non-linear. This attribute is often specified by instrument manufacturers. Although typical specification values are sufficient for attenuation coefficient measurements, they are not sufficiently stringent to allow accurate characterization of MFD over the entire fibre length. Bi-directional backscatter traces are required to characterize MFD.

This method is most often used in manufacturing, where the fibre design is well known. The latter methods shall be used to resolve disputes in value. Periodic validation of the results of this method is recommended.

D.1 Apparatus

D.1.1 OTDR

The equipment is described in Method C – Backscattering, of IEC 60793-1-40. The actual centre wavelengths of the OTDR should be known to within 2 nm for best results. An error of 2,5 nm will cause about a 0,025 µm error in the MFD when wavelengths in the 1 310 nm and 1 550 nm region are used.

D.1.2 Optional auxiliary switches

Various optical switching schemes can be used to make this method more efficient. Figure D.1 illustrates an example in which an OTDR with lasers at two wavelengths is employed to carry out bi-directional backscattering measurements. The two reference fibres allow characterization of both ends of the fibre under test.

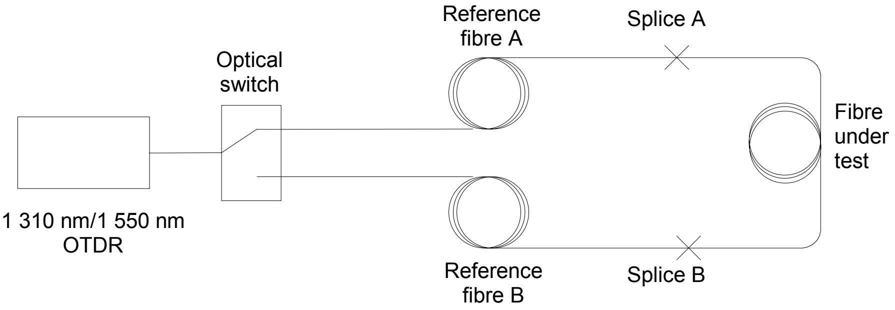


Figure D.1 – Optical switch arrangement

NOTE The splices indicated on figure D.1 can be butt joints. The splices must be stable for the duration of the measurement.

D.1.3 Optional computer

A computer, used for evaluating the loss across the splices, is recommended.

D.1.4 Test sample

The sample is a type B single-mode fibre, wound on a reel or in a cable, long enough to exceed (or positioned beyond) the dead zone of the OTDR, with both ends accessible, as described in the backscatter test of IEC 60793-1-40.

D.1.5 Reference sample

Use a single-mode fibre which has been measured for MFD at one or more wavelengths. Two reference fibres, one for each end of the specimen, may be used.

The reference fibre is typically of the same design as the fibre under test and is of a length sufficient to avoid the OTDR dead-zone. If the reference fibre is not of the same design as the fibre under test, a mapping of the values generated by this method and the values generated by a primary method shall be completed.

D.2 Procedure

D.2.1 Orientation and notation

This method describes the characterization of position A of Figure D.1. The notation of this section can be inverted for characterization of position B. The backscatter loss across position A is measured by launching light of one or more wavelengths into both reference fibre A and reference fibre B.

For this procedure, the following symbols are used:

λ_j	is a particular wavelength;
RFA	is reference fibre A;
RFB	is reference fibre B;
$L_A(\lambda_j)$	is the loss across splice A when launching λ_j through RFA;

$L_B(\lambda_j)$ is the loss across splice A when launching λ_j through RFB;

$W_A(\lambda_j)$ is the measured MFD at λ_j at the end of RFA;

$W_S(\lambda_j)$ is the MFD at λ_j derived from this method for the specimen.

Figures D.2 and D.3 show these loss values on two backscatter traces.

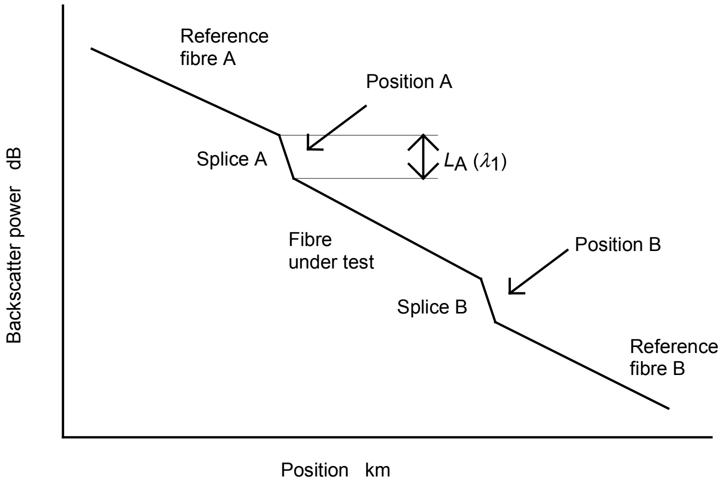


Figure D.2 – View from reference fibre A

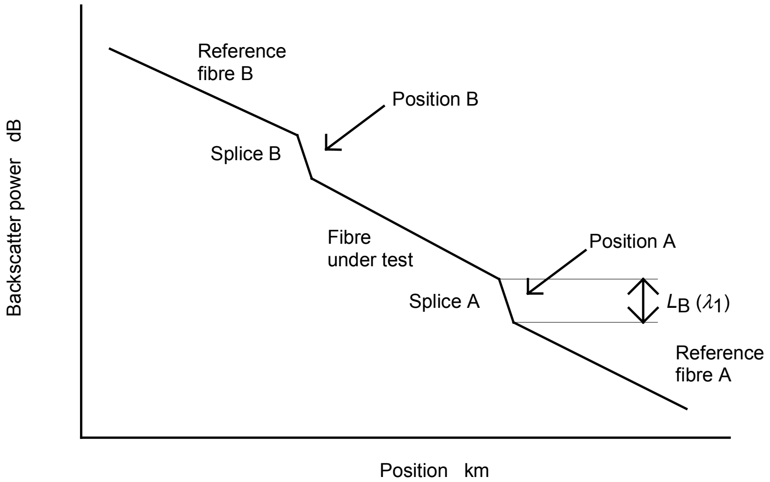


Figure D.3 – View from reference fibre B

D.2.2 The loss across splice A is measured using C.3.6 of IEC 60793-1-40 when launching light at λ_1 from RFA. The result is recorded as $L_A(\lambda_1)$. The loss across splice A is measured using C.3.6 of IEC 60793-1-40 when launching light at λ_1 from RFB. The result is recorded as $L_B(\lambda_1)$.

D.3 Calculations

D.3.1 Reference fibre MFD

The MFD of reference fibre A should be measured at each desired wavelength.

D.3.2 Computation of the specimen MFD

For each desired wavelength, λ_j, the difference in loss between RFA and RFB views is computed as follows:

$$\Delta L(\lambda_j) = L_A(\lambda_j) - L_B(\lambda_j) \tag{D.1}$$

The MFD of the specimen at λ_j is computed as follows:

$$W_S(\lambda_j) = W_A(\lambda_j) 10^{[g_j \Delta L(\lambda_j) + f_j]/20} \tag{D.2}$$

The parameters g_j and f_j allow improvements in the result. For a given product design, g_j and f_j values that optimize accuracy may be determined experimentally. Alternatively, g_j and f_j may be set to values of 1 and 0, respectively.

D.3.3 Validation

Figure D.4 illustrates a validation plot.

A sample of the population of the fibre design is measured with both a primary method and this method. The sample should cover a broad range of MFD and cut-off values.

The values of this method are plotted against the values from the primary method to verify that an essentially linear relationship is present. The slope of the line should be close to unity and the intercept should be close to zero. The best test for non-unit slopes is to correlate the paired differences with the paired totals. If the correlation is not significant, the slope is not significantly different than 1. Bias, or non-zero intercept is addressed below.

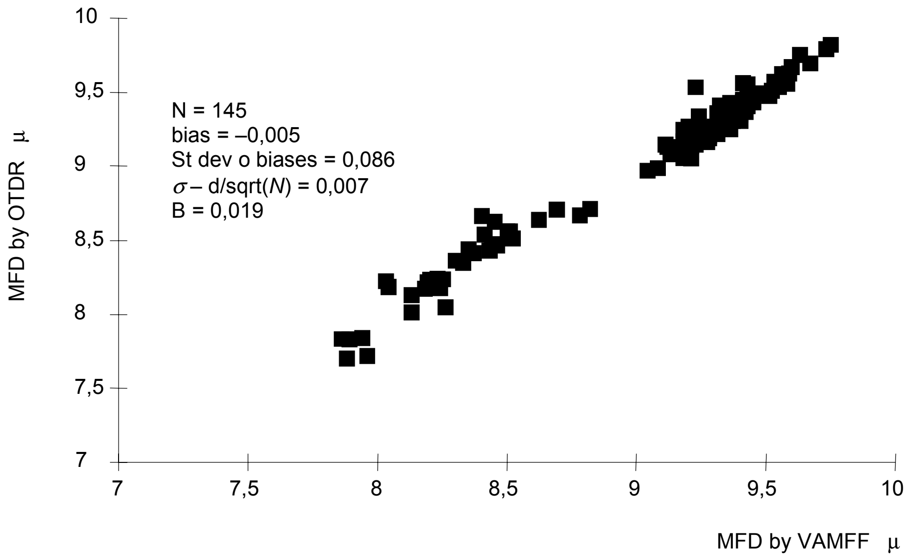


Figure D.4 – Validation example – Comparison of methods

The paired difference, d_i, between the values of this method and the primary methods is computed for each specimen, indexed with i, from 1 to N. A histogram is formed of these paired differences and the average, $\overline{d}$, and standard deviation, σ_d, of these differences are computed. The empirical accuracy is represented as follows:

$$B = | \overline{d} | + 2\frac{\sigma_d}{\sqrt{N}} \tag{D.3}$$

NOTE If *B* is too large, i.e. larger than expected between two instruments using other methods from this standard, refinement of the equations or of the procedure is recommended. A typical maximum value of *B* is 0,1 µm.

Annex E
(informative)

Sample data sets and calculated values

The following tables represent sample data and calculated values obtained from annexes A, B and C, respectively.

E.1 Method A – MFD by direct far-field scan

Table E.1 – Sample data, method A – MFD by direct far-field scan

Angle °	Folded power	Angle °	Folded power
0,000	1,000 00	9,405	0,048 47
0,495	0,986 26	9,900	0,039 11
0,990	0,944 69	10,395	0,031 55
1,485	0,881 28	10,890	0,025 58
1,980	0,802 91	11,385	0,020 59
2,475	0,713 44	11,880	0,016 59
2,970	0,621 16	12,375	0,013 35
3,465	0,533 03	12,870	0,010 77
3,960	0,452 02	13,365	0,008 65
4,455	0,378 06	13,860	0,006 97
4,950	0,313 73	14,355	0,005 59
5,445	0,258 48	14,850	0,004 47
5,940	0,211 16	15,345	0,003 56
6,435	0,171 70	15,840	0,002 83
6,930	0,139 50	16,335	0,002 24
7,425	0,113 30	16,830	0,001 79
7,920	0,091 99	17,325	0,001 45
8,415	0,074 47	17,820	0,001 13
8,910	0,060 09	18,315	0,000 87

E.2 Method B – MFD by variable aperture in the far field

Details of the calculation method may cause differences in computed value on the order of 0,01 µm.

Table E.2 – Sample data set, method B – MFD by variable aperture in the far field

θ_i °	Power	θ_i °	Power
1,273	0,085 72	10,367	0,708 23
2,201	0,208 64	11,172	0,714 50
2,930	0,312 50	11,944	0,719 71
3,820	0,423 22	13,216	0,725 10
4,631	0,509 08	14,879	0,729 71
5,403	0,567 77	16,671	0,733 06
6,271	0,613 60	18,275	0,734 74
7,107	0,646 90	20,042	0,735 82
7,776	0,667 85	21,788	0,735 84
8,663	0,686 43	23,478	0,736 16
9,558	0,699 63	–	–
Wavelength: 1 300 nm. Calculated MFD: 8,163 µm.			

E.3 Method C – MFD by near-field scan

A sample data set and the calculation of MFD appears in table E.3.

Table E.3 – Sample data set, method C – MFD by near-field scan

r µm	$f^2(r) / I(0)$	r µm	$f^2(r) / I(0)$
0,000	1,000 00	10,817	0,001 97
1,082	0,890 27	11,899	0,000 88
2,163	0,635 61	12,981	0,000 36
3,245	0,350 31	14,063	0,000 15
4,327	0,166 87	15,144	0,000 06
5,409	0,078 26	16,226	0,000 02
6,490	0,037 35	17,308	0,000 00
7,572	0,017 52	18,389	0,000 00
8,654	0,008 72	19,471	0,000 00
9,736	0,004 33	20,553	0,000 00
Wavelength: 1 300 nm. Calculated MFD: 10,76 µm.			

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